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NEW VERSION OF THE HUMIDITY SLIDE-RULE

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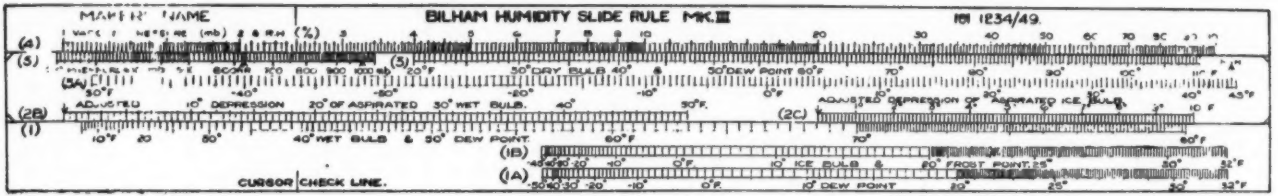
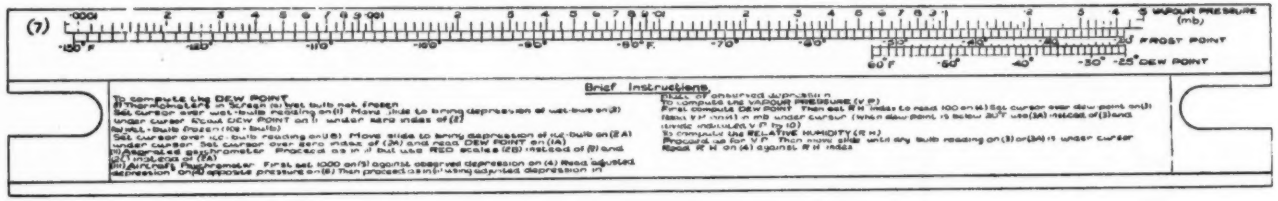
Summary.—By extending the scales to low temperatures and by making some changes in the general lay-out, provision is made in the humidity slide-rule Mk. III for computing dew points down to −50°F., using data derived from surface observations, aircraft observations or radio-sonde. Scales for the computation of vapour density, vapour pressure, mixing ratio, relative humidity and hoar-frost point are also provided.

History.—In the first version of the humidity slide-rule,* provision was made for computing the usual hygrometric elements from psychrometric data within the ranges: dry bulb, 10° to 110°F.; wet bulb and dew point, 5° to 80°F. For temperatures below freezing point the dew point and relative humidity were defined with reference to saturation over supercooled water. This slide-rule was given the nomenclature Mk. I. In a tropical model, Mk. IA, the dry-bulb and wet-bulb scales were extended to 140°F. and 95°F. respectively. In 1940, the Meteorological Office changed its practice in regard to values below freezing point, and defined the relative humidity with reference to ice instead of supercooled water. At the same time it was decided to substitute the hoar-frost point (*i.e.* the temperature of saturation with respect to ice) for the true dew point (*i.e.* the temperature of saturation with respect to supercooled water). To cover these changes new patterns Mk. II and Mk. IIA (for the tropics) of the humidity slide-rule were introduced.

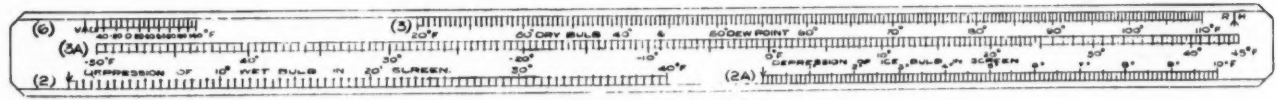
In 1947 the Twelfth Conference of Directors at Washingon agreed to define dew point and relative humidity with respect to water at all temperatures. The implementation of this decision meant that the Meteorological Office had to return to its pre-1940 practice. If no other considerations had been involved the action necessary as regards slide-rules would have been simply to re-introduce Mk. I and IA in place of Mk. II and IIA. The situation was, however, complicated by another factor. The Conference of Directors at Washington in 1947 had also recommended, as the basis of hygrometric computations, new tables of saturation vapour pressure (the Goff-Gratch Tables) which differed from those upon which the 1935 slide-rule was based.

*BILHAM, E. G.; A humidity slide-rule. *J. Sci. Instr., London*, **12**, 1935, p. 318, and BILHAM, E. G.; A slide-rule for hygrometric calculations. *Met. Mag., London*, **70**, 1935, p. 254.





BACK OF STOCK WITH SLIDE REMOVED.



REVERSE OF SLIDE.

FIG. I.—LAY-OUT OF HUMIDITY SLIDE-RULE MK. III

Before slide-rules to meet the new international requirements could be obtained it thus became necessary to revise the specification. It was decided to undertake a more extensive revision so that the new design should provide means of reducing psychrometric observations made on aircraft at pressure levels up to 300 mb. and also for the conversion to dew point of relative-humidity observations provided by radio-sondes. These requirements are met in the Mk. III version now to be described. The necessary downward extension of the temperature scales gives the new pattern a further advantage over its predecessors, namely that it is capable of handling all but the most extreme readings obtained in high, middle and low latitudes.

In the new slide-rule the scales have been re-numbered, and there are many other changes from the previous design. The following description has therefore been written *ab initio*, no acquaintance with previous patterns being assumed.

General arrangements.—Following conventional practice the slide-rule (Fig. 1) comprises a fixed portion, the " stock ", 11 in. long by 1½ in. wide, a sliding portion the " slide ", and a cursor upon which is engraved a fine line at right angles to the axis of the stock. The slide is reversible and scales are engraved on both the front and the back. The remainder of the scales for most hygrometric computations appear on the front of the stock. On the back of the stock logarithmic scales of saturation vapour pressure for low-temperature ranges appear at the top, and the remainder of the space is occupied with abbreviated working instructions.

Imagining the slide-rule to be divided into two by a central axial line, the lower part is used for computing the dew point from psychrometric observations, and the upper part for converting dew point to vapour pressure and for computing relative humidity, mixing ratio and vapour density, or for inter-conversions of these parameters. There is provision also on the upper part of the rule for applying the pressure correction required when computing dew point from psychrometric observations provided by aircraft or high-level stations.

With one exception mentioned below the slide-rule provides, to three significant figures over most of the range, a direct solution of the relevant equation as internationally agreed. Unfortunately, there is as yet no international agreement as to the values of the so-called psychrometric constants. It is thus still possible for observers in different countries to derive slightly different values of the dew point, etc., from the same readings of dry-bulb and wet-bulb temperatures. The scales concerned are therefore based on values of the constants adopted by the Meteorological Office.

The exception referred to relates to the definition of relative humidity. Prior to the Conference of Directors at Washington in 1947 the relative humidity was defined as the ratio of the vapour pressure to the saturation vapour pressure at dry-bulb temperature, multiplied by 100. This was changed at Washington by substituting mixing ratio for vapour pressure. The numerical result is, at temperatures occurring in meteorological practice, very nearly the same with both definitions. The results agree at 100 per cent. and 0 per cent., and between these extremes the " Washington " value is the lower. For a given dry-bulb temperature the maximum difference occurs at 50 per cent. relative humidity where, for a total pressure of 1000 mb., it is ½ per cent. at 64°F. and 2 per cent. at 107°F. The grounds for changing the definition have not been made clear and have not been considered strong enough to justify a change in Meteorological Office procedure. As in previous designs therefore,

the new slide-rule provides for the determination of relative humidity as the percentage ratio of the actual vapour pressure to the saturation vapour pressure at dry-bulb temperature.

Computation of dew point from psychrometric data.—The basis of computation is the simplified Regnault formula adopted by the Meteorological Office

$$x = f - A\frac{p}{p_0}(t - t') \qquad .. \quad (1)$$

where t = dry-bulb temperature
t' = wet-bulb temperature
} in degrees Fahrenheit.

p = pressure at time of observation in millibars.

p_0 = standard pressure (1000 mb.) to which the value of A applies.

A = the psychrometric constant, the value of which depends upon the speed of air flow over the thermometers and upon whether the wet bulb is covered with water or ice.

f = the saturation pressure at the temperature of the wet-bulb, in millibars.

x = the vapour pressure at the time of observation, in millibars.

It is assumed that at temperatures of 32°F. or below the wet bulb becomes an ice bulb; in these circumstances f is the saturation pressure with respect to ice at temperature t'.

The dew point is the temperature for which x is the saturation pressure with respect to water, at all temperatures.

Following the practice of "Hygrometric Tables"* the values of the constant A for a pressure of 1000 mb. are

	Wet bulb	Ice bulb
For thermometers in standard screens without artificial aspiration	0·444	0·400
For aspirated thermometers (Assmann psychrometer, aircraft thermometers, whirling psychrometers)	0·37	0·33

Surface observations.—Except when the temperature and humidity are extremely low small variations in the quantity Ap/p_0 do not substantially affect the computed value of x. It is therefore normal practice to ignore variations from unity in the factor p/p_0 in the case of stations not more than about 3,000 ft. above sea level. For land stations below this level, and ship stations, equation (1) therefore takes the simple form

$$x = f - A(t - t') \qquad .. \quad (2)$$

If now we write

$a_w(t)$ = saturation pressure with respect to water at any temperature t

$a_i(t)$ = saturation pressure with respect to ice at any temperature t

t_d = dew point

we have $x = a_w(t_d)$ at all temperatures
$f = a_w(t')$ for $t' > 32$°F.
$f = a_i(t')$ for $t' < 32$°F.

and equation (2) takes the following forms.

*London, Meteorological Office. Hygrometric Tables. 4th edn., London, 1940.

'(i) Thermometers in standard screens

Wet bulb above freezing point

$$a_w(t_d) = a_w(t') - 0{\cdot}444\ (t - t') \quad .. \quad (3)$$

Wet bulb at or below freezing point

$$a_w(t_d) = a_i(t') - 0{\cdot}400\ (t - t') \quad .. \quad (4)$$

(ii) Aspirated thermometers

Wet bulb above freezing point

$$a_w(t_d) = a_w(t') - 0{\cdot}37\ (t - t') \quad .. \quad (5)$$

Wet bulb at or below freezing point

$$a_w(t_d) = a_i(t') - 0{\cdot}33\ (t - t') \quad .. \quad (6)$$

The four equations (3) to (6) are the bases of computation of dew point from dry-bulb and wet-bulb temperatures under the four sets of conditions postulated.

To solve any of these equations (say equation (3)) mechanically we need, to start with, a temperature scale so divided that the distance from an arbitrary zero to the division marked t is proportional to $a_w(t)$. Call this distance $B.a_w(t)$, B being the length corresponding to one millibar on the scale. If now we start at the point on the scale marked t' and move backward a distance $0{\cdot}444\ B(t - t')$ we see from equation (3) that we arrive at a point whose distance from the zero is $B.a_w(t_d)$, that is to say we arrive at the dew point.

Turning now to the actual slide-rule the scale of $a_w(t)$ is scale (1), and the operation of subtracting the quantity $0{\cdot}444\ (t - t')$ is performed with the aid of scale (2) which is so divided that the length of one degree is equal to $0{\cdot}444$ times the length corresponding to one millibar on scale (1).

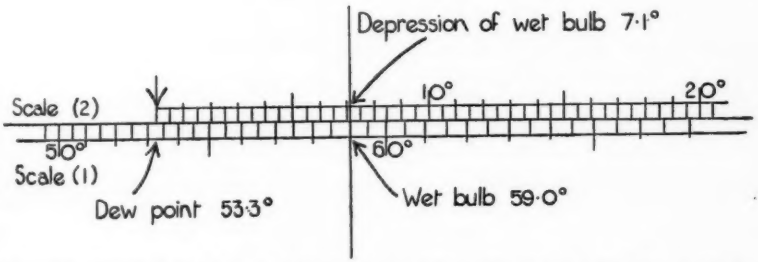


FIG. 2—COMPUTATION OF DEW POINT; WET-BULB READING ABOVE FREEZING POINT
Thermometers in screen

To deal with aspirated thermometer readings (equation (5)) we require a different " depression " scale, *i.e.* one in which the length of one degree is 0·37 times the length corresponding to one millibar on scale (1). This is scale (2B), which is coloured red to distinguish it readily from scale (2).

For ice-bulb readings (equations (4) and (6)) the procedure is slightly more complicated, because we need two saturation vapour-pressure scales, one with respect to supercooled water and the other with respect to ice, both graduated from the same arbitrary zero. Taking equation (4), we start from the point t' on the ice-saturation scale (1B) and step back a distance corresponding to $0{\cdot}400\ (t - t')$ on the depression scale (2A). This, if read on scale (1B) would give the hoar-frost point, but as we require the dew point the setting is transferred to the water-saturation scale (1A) placed immediately below it. The

corresponding depression scale for an aspirated ice bulb is (2C). In order to cope with low temperatures where the change of saturation vapour pressure per degree of temperature is very small, the scale equivalent of one millibar in scales (1A) and (1B) is much greater than in scale (1) and the depression scales (2A) and (2C) are of course expanded proportionately.

The working instructions for the determination of dew point are thus as follows

(i) Thermometers in screen. Wet bulb not frozen (Fig. 2)
Set cursor over wet-bulb reading on (1)
Move slide to bring depression of wet bulb on (2) under cursor
Read DEW POINT on (1) under zero index of (2).

(ii) Thermometers in screen. Wet bulb frozen (ice-bulb) (Fig. 3)
Set cursor over ice-bulb reading on (1B)
Move slide to bring depression of ice bulb on (2A) under cursor
Set cursor over zero index of (2A) and read DEW POINT on (1A)

(iii) Aspirated psychrometer. Proceed as in (i) and (ii) but use RED scales (2B) instead of (2) and (2C) instead of (2A).

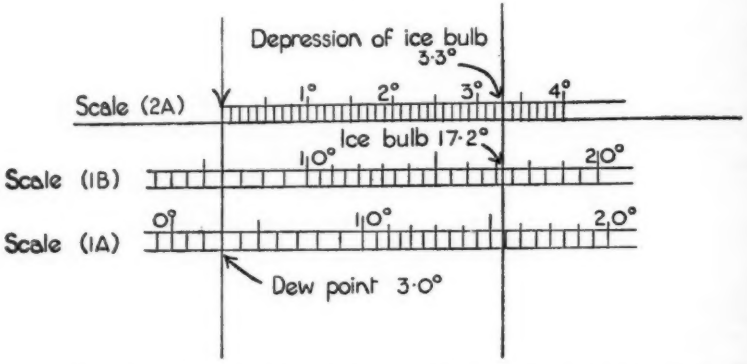


FIG. 3—COMPUTATION OF DEW POINT; WET-BULB READING BELOW FREEZING POINT (ICE BULB)
Thermometers in screen

Aircraft observations.—Readings on aircraft flying at low levels (*e.g.* on the low-level legs of meteorological reconnaissance flights) are dealt with in the same way as for aspirated psychrometers. For higher levels the "adjusted" depression of wet bulb $p(t - t')/1{,}000$ must first be evaluated, using scales (4) and (5) on the upper part of the rule. These are ordinary logarithmic scales. Set 1,000 on scale (5) against the observed depression on scale (4). Set the cursor over p (the pressure at the level of observation) on scale (4) and read the adjusted depression under the cursor on scale (5). If the depression is very small, *e.g.* 2·0°F. or less, multiply by 10 first and then divide the answer by 10. The procedure is then exactly the same as for an aspirated psychrometer, the adjusted depression being used instead of the actual depression.

High-level observations with un-aspirated thermometers.—First obtain the adjusted depression, being careful to note that p is the pressure corrected to station level. Then proceed as described above for thermometers in screens, using the adjusted depression in place of the actual depression.

For insertion in synoptic messages it suffices to read the dew point to the nearest whole degree. When, however, the dew point is required as the first step in the computation of other parameters it is advisable to note the value to the nearest tenth of a degree, and the scales are sufficiently open for this to be practicable in most cases.

Computation of vapour pressure and relative humidity. Scale (3) on the upper edges of the slide is a temperature scale in which the argument is the logarithm of the saturation vapour pressure over water. If the slide is adjusted so that the index marked R.H. reads 100 on the two-cycle logarithmic scale (4) then the reading on (4) opposite any temperature graduation on (3) is the saturation vapour pressure in millibars for that temperature. Consequently with the R.H. index set to 100 the vapour pressure x is at once obtained on scale (4) by setting the cursor over the dew point on (3). Leaving the cursor so set, if the dry-bulb temperature on (3) is brought under the cursor by moving the slide, the R.H. index now indicates the relative humidity on scale (4).

The procedure of the previous paragraph is applicable when the dew point is above 20°F. For lower temperature ranges scale (3A) is used in place of scale (3). The basis of graduation of scale (3A) is the same as in scale (3) but its zero is displaced 5 in. to the right, so that when the R.H. index reads 100 and the cursor is placed over any graduation on scale (3A), the reading on scale (4) under the cursor is ten times the saturation vapour pressure in millibars for that temperature. The indicated value of x read on (4) when the cursor is set over the dew point on (3A) must therefore be divided by ten. The indicated value of the relative humidity is however correct as it stands, provided the dry-bulb setting is also made on scale (3A).

It occasionally happens that a dew point below 20° occurs with a dry bulb above the upper limit of scale (3A), *i.e.* 45°F. In such a case the procedure is as follows : using scale (3A), evaluate the vapour pressure, remembering to divide the indicated value by ten. Set the cursor over the (true) vapour pressure on scale (4) and bring the dry-bulb reading on scale (3) under the cursor; read the relative humidity against the R.H. index on scale (4).

Computation of mixing ratio, specific humidity and vapour density. —When the vapour pressure x has been computed the mixing ratio r given by the formula

$$r = 0{\cdot}62197 \frac{x}{p - x}$$

can readily be evaluated, using scales (4) and (5). The position of the constant multiplier is shown on scale (5) by an index lettered M.R. Set the cursor over the value of x on scale (4); bring the value of $(p - x)$ on scale (5) under the cursor and read the value of r on scale (4) against the index M.R. For low values of x multiply by 10 in the numerator only before computing and then divide the answer by 10. The value of r is in grams per kilogram.

The specific humidity (q) is given by

$$q = 0{\cdot}62197 \frac{x}{p}$$

and is calculated in the same way, the only difference being the substitution of p for $(p - x)$ in the division. As x is always small compared with p the two quantities rarely differ by more than two or three per cent.

The vapour density (d_v) is given by

$$d_v = 216{\cdot}7\,\frac{x}{T}$$

where T is the temperature on the absolute scale. A special scale (6) is provided on the back of the slide for computing this parameter. Set the cursor over the value of x on scale (4) and bring the value of the dry-bulb temperature on scale (6) under the cursor; read the value of d_v on scale (4) in grams per cubic metre, against the index marked V.D.

Radio-sonde observations.—Radio-sondes include devices for determining the pressure, temperature and relative humidity at various levels in the free atmosphere. The humidity element is operated by a hygrometric material (gold-beater's skin in the British version) the dimensions of which respond to variations in the relative humidity, and it has been established that at temperatures below freezing point the controlling factor is the relative humidity with respect to supercooled water. Values of vapour pressure and dew point can therefore be readily derived from radio-sonde observations of temperature and relative humidity by making use of scales (3), (3A) and (4).

Set the R.H. index to the observed value of the relative humidity on scale (4). If the temperature (t) is above 45° set the cursor over t on scale (3) and read the vapour pressure (if wanted) on scale (4). Leaving the cursor in this position set the R.H. index to 100 on scale (4). The dew point is then read under the cursor line.

For values of t below 45° use scale (3A) instead of scale (3). The indicated vapour pressure has in this case to be divided by 10, but the dew point is correctly shown on scale (3A).

As scale (3) does not read below 20° the procedure described above will not work when t is above 45° and the relative humidity is less than about 40 per cent. Unless the relative humidity is less than 10 per cent. it will however be possible to read the vapour pressure on scale (4). The dew point can then be evaluated by the following artifice. Multiply the vapour pressure by 10 and set the cursor over the value on scale (4). Leaving the cursor in this position set the R.H. index to 100 and read the dew point under the cursor on scale (3A). If the relative humidity is less than 10 per cent. proceed as follows. First set the R.H. index to ten times the observed relative humidity on scale (4). Set the cursor over t on scale (3), read the vapour pressure on scale (4) and divide by 10 to obtain the true vapour pressure (if wanted). Leaving the cursor in this position, set the R.H. index to 100 and read the dew point on scale (3A).

Conversion of hoar-frost point to dew point.—The Dobson-Brewer frost-point hygrometer provides an accurate means of measuring the hoar-frost point directly on an aircraft. To convert the reading to dew point set the cursor over the hoar-frost point reading on scale (1B) and read the dew point under the cursor on scale (1A). Having obtained the dew point any other parameter may be computed by the procedures described on p. 71.

Standard saturation vapour pressures.—The standard Goff-Gratch values of saturation vapour pressure may be obtained by estimation to two or three significant figures by the following procedures.

Saturation with respect to water

Range 20° to 110°F. Set the R.H. index to 100 on scale (4) and place

the cursor over the temperature on scale (3). Read the saturation vapour pressure on scale (4) under the cursor.

Range —50° to 20°F. With R.H. index set to 100, set cursor over the temperature on scale (3A). Read scale (4) and divide by 10.

Range −60° to −50°F. Set cursor over the temperature on the dew-point scale on back of stock and read the saturation vapour pressure under the cursor on scale (7).

Saturation with respect to ice

Range 22° to 32°F. Set cursor over temperature on scale (1B) and read dew point on scale (1A). With R.H. index set to 100 on (4), set cursor over dew point on scale (3) and read saturation vapour pressure under the cursor on scale (4).

Range −20° to 22°F. Same procedure as above but set cursor over dew point on scale (3A), read on scale (4) and divide by 10.

Range −130° to −20°F. Set cursor over the temperature on the frost-point scale on back of stock and read the saturation vapour pressure under the cursor on scale (7).

Miscellaneous hygrometric computations.—Most hygrometric computations involve either the inter-conversion of parameters or the determination of changes of relative humidity resulting from changes of temperature or moisture content at constant pressure.

A quantity frequently required in evaporation problems is the saturation deficit. This parameter, expressed in millibars, is obtained by subtracting the vapour pressure from the saturation vapour pressure at the temperature of observation.

Example. Air at 70°F., relative humidity 75 per cent., determine the saturation deficit in millibars. Set R.H. index to 25 (= 100 − relative humidity) on scale (4). Set cursor over 70° on scale (3) and read the saturation deficit under the cursor on scale (4). Answer 6·3 mb. Use scale (3A) if the temperature is below 45° and divide the answer by 10.

If the saturation deficit is required in grams per cubic metre it is necessary first to determine the vapour density by the use of scale (6) (see p. 72), giving the answer 13·8 gm./m.^{3} Next determine the saturation vapour density by the following method. Set the R.H. index to 100 and set the cursor over the temperature (70°F.) on scale (3). Without moving the cursor bring temperature 70°F. on scale (6) under the cursor. Read the saturation vapour density (18·5) on scale (4) opposite the vapour-density index. The saturation deficit is then equal to 18·5 − 13·8 = 4·7 gm./m.^{3}

The following example illustrates a typical application to problems in which constancy of vapour pressure may be assumed.

Example. Air at 45°F., relative humidity 90 per cent., is warmed to a temperature t°F. without adding or removing water, determine the new value of the relative humidity for various values of t. Set R.H. index to 90 and place cursor over 45°F. on scale (3). This gives the vapour pressure 9·2 mb. on scale (4) which is unaltered during the warming. Bring any desired value of t on scale (3) under the cursor and the R.H. index will then show the corresponding value of the relative humidity, *e.g.* $t = 50°$,

relative humidity = 75 per cent.; $t = 60°$, relative humidity = 52 per cent.; $t = 65°$, relative humidity = 43·5 per cent.

Acknowledgements.—The detailed specification and drawings for the Mk. III humidity slide-rule were prepared in the General Instruments Branch of the Meteorological Office under the direction of Mr. O. M. Ashford from a sketch design provided by the author. The onerous task of carrying out the computations for specifying the exact positions of all scale divisions was performed by Mr. R. H. Collingbourne.

ELEMENTS OF ANOMALOUS RADIO PROPAGATION

By E. KNIGHTING, B.Sc.

The distance of the optical horizon of an observer at height h is $\sqrt{(2ha)}$ where a is the radius of the earth, and it might be expected that the range of an electromagnetic wave propagated at height h would approximately have the same range. In the case of large wave-lengths, *i.e.* radio waves of the order of hundreds of metres it is known that, owing to reflections at various layers (Kennelly-Heaviside, Appleton layers), the range is very much extended. However, with a directed energy beam, which does not suffer reflection at these layers owing to the small angle of propagation, the range might be expected to approximate to $\sqrt{(2ha)}$. There is a diffraction zone below the horizon which might account for small increases in the range.

The practical use of radar showed that ranges very much greater than $\sqrt{(2ha)}$ were encountered. For example English coastal radars reported observations of the European coast, well beyond the optical horizon, and at Bombay a 1½ m. radar at a height of 255 ft. and an optical horizon of about 25 miles observed shipping up to ranges of 500 miles and occasionally more. It is the explanation of the possibility of such large ranges that we are concerned with in the following paragraphs.

The refractive index of the atmosphere.—The path of an electromagnetic wave depends upon the dielectric properties of the medium. The dielectric constant of water vapour is given experimentally[1*†] by

$$\epsilon - 1 = 180 \times 10^{-6}\left(1 + \frac{5580}{T}\right)\frac{p}{T}$$

where T is the absolute temperature and p the pressure of water vapour in millimetres of mercury.

The dielectric constant for dry air is given experimentally by

$$\epsilon - 1 = 210 \times \frac{P}{T} \times 10^{-6}$$

where P is the pressure of the air, and, since dielectric constants are additive, the dielectric constant for moist air is

$$\epsilon - 1 = \left\{210\,\frac{P}{T} + 180\left(1 + \frac{5580}{T}\right)\frac{p}{T}\right\} \times 10^{-6}$$

where P, p are the partial pressures of dry air and water vapour. Since the refractive index n is given by $n = \sqrt{\epsilon}$, the refractive index of moist air is given with sufficient accuracy by

$$n - 1 = \frac{79}{T}\left\{P - \frac{e}{7} + \frac{4800e}{T}\right\} \times 10^{-6}$$

*The index numbers refer to the list of references on p. 81.
†Results of many workers.

where P is now the total pressure, e the vapour pressure in millibars and T the absolute temperature.

A rough calculation, taking $T \triangleq 300°$A., $P \triangleq 1000$ mb., $e \triangleq 10$ mb. shows that $(n - 1)$ is of the order 300×10^{-6} in the atmosphere. For ease of calculation a new unit m is introduced, given by

$$m = (n - 1) \times 10^6 = \frac{79}{T}\left\{P - \frac{e}{7} + \frac{4800e}{T}\right\}$$

and the new unit is known as an M-unit, being measured in millionths.

In the atmosphere there is a general lapse of m, the mean lapse being $1{\cdot}3M/100$ ft., and an atmosphere with such a lapse is often termed a standard atmosphere.[2]†

Ray curvature and modified refractive index.—From the principle of least time it is easily shown that in "flat earth" co-ordinates, where h is the height above the earth's surface, x the horizontal distance, n the refractive index and a the earth's radius, the differential equation of the ray path is

$$0 = \frac{d^2h}{dx} - \left\{\frac{1}{n}\cdot\frac{dn}{dh} + \frac{2}{a+h}\right\}\left(\frac{dh}{dx}\right)^2 - \left\{\frac{1}{n}\cdot\frac{dn}{dh}\left(1 + \frac{h}{a}\right) + \frac{1}{a}\right\}\left(1 + \frac{h}{a}\right)$$

In many radar problems, particularly in long-range detection problems, dh/dx, which is the inclination of the ray to the horizon, is small and the second term can be neglected. The multiplying factor $(1 + h/a)$ in the third term is little different from unity near the earth's surface.

As we have seen above, n only varies by 300 parts in a million and may be taken as unity.

The equation then reduces to

$$\frac{d^2h}{dx^2} - \left(\frac{dn}{dh} + \frac{1}{a}\right) = 0 \qquad \ldots (1)$$

The ray curvature is simply $-d^2h/dx^2$ with dh/dx small, and hence referred to a flat earth the ray curvature K is

$$K = -\left(\frac{dn}{dh} + \frac{1}{a}\right) \qquad \ldots (2)$$

and the absolute curvature is, taking into account the earth's curvature,

$$K' = -\frac{dn}{dh} \qquad \ldots (3)$$

We can look at equation (2) in a slightly different way, for the curvature referred to the earth is that produced by a refractive index $(n + h/a)$. We define, therefore, a modified refractive index

$$M' = \left(n + \frac{h}{a} - 1\right) \times 10^{-6}$$

in M-units. It is this modified refractive index that is used in practical radio meteorological work.

Again returning to (2), if dn/dh is constant, if we put

$$\frac{1}{ka} = \frac{dn}{dh} + \frac{1}{a}$$

then the ray curvature with respect to an earth of radius ka is zero and the ray can be drawn as a straight line. For the value dn/dh quoted then $adn/dh \triangleq -\frac{1}{4}$ and the straight-line rays are drawn on an earth of radius $4a/3$. ka is termed the equivalent earth radius, and varies from place to place with the

†A standard atmosphere has not been agreed[2].

lapse rate of n (assumed constant). Fig. 1 shows rays referred to the earth, the equivalent earth and the flat earth.

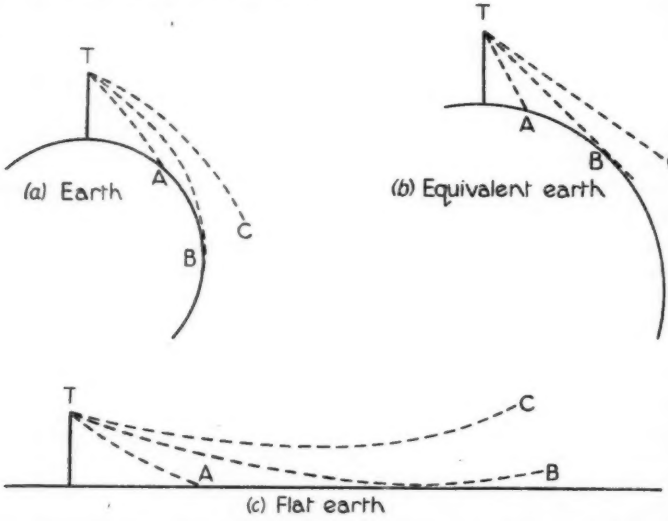


FIG. 1—REPRESENTATION OF RAYS ON (*a*) EARTH (*b*) EQUIVALENT EARTH (*c*) FLAT EARTH

TA is ray within horizon, TB is horizon ray, TC does not reach earth

Lapse rate of refractive index.—We see that the variation of refractive index of the atmosphere with height is an important factor in refracting electro-magnetic energy. From (2) if $dn/dh + 1/a < 0$ then the ray is bent towards the earth. In terms of the modified refractive index M', the ray is bent towards the earth if there is an M' lapse. We may express this in terms of meteorological variables through the equation

$$M' - \frac{h}{a} = m = 10^6 (n - 1) = \frac{79}{T}\left\{p - \frac{e}{7} + \frac{4800e}{T}\right\}$$

first remarking that the term $e/7$ is small compared with the other terms.

Pressure effect.—

$$\left(\frac{dm}{dh}\right)_{T,e} = \frac{79}{T}\frac{\partial P}{\partial h}$$

and since $\partial P/\partial h = -g\rho$, near the surface this is a constant contribution, approximately $1M/100$ ft.

Temperature effect.—

$$\left(\frac{dm}{dh}\right)_{P,e} = -\frac{79}{T^2}\left\{P + \frac{9600e}{T}\right\}\frac{\partial T}{\partial h}$$

The temperature effect thus depends on P and the moisture content. An estimate of $(dm/dh)_{P,e}$ for $T = 288°$A., $P = 1000$ mb., $e = 10$ mb. is

$$\left(\frac{dm}{dh}\right)_{P,e} \triangleq -1{\cdot}25\frac{\partial T}{\partial h}$$

For bending a ray towards the earth (earth's radius $= 6{\cdot}4 \times 10^6$ m.)

$$1{\cdot}25\frac{\partial T}{\partial h} > \frac{1}{6{\cdot}4} \text{ or } \frac{\partial T}{\partial h} > \frac{1}{8}°\text{C./m.}$$

which is equivalent to 7°F./100 ft. Thus an inversion of 7°F. per 100 ft. is capable of bending the ray down towards the earth.

Humidity effect

$$\left(\frac{dm}{dh}\right)_{P,T} = \frac{79}{T} \times \frac{4800}{T}\frac{\partial e}{\partial h}$$

We express the humidity in terms of a mixing ratio q grams of water vapour per kilogramme of dry air, and at 288°A. find that a lapse rate of mixing ratio greater than 2/3 gm./Kg./100 ft. is necessary to produce downard bending of the rays. If we denote by α and β the critical values for temperature and humidity gradients obtained above and by T', q' the temperature and humidity gradients, then the combined effect necessary for downward ray bending is $T'/\alpha + q'/\beta > 1$ or in the cases considered:—

$$\frac{\text{Temperature gradient (per 100 ft.)}}{7} + \frac{\text{Humidity lapse (per 100 ft.)}}{2/3} > 1$$

In the rest of the paper, the units used will be degrees Fahrenheit and feet.

Observations of gradients exceeding critical values.—The necessary gradients for bending rays towards the earth as found above are large and we must inquire whether such gradients have in actual fact been found.

Temperature inversions over land.—The experiments carried out at Porton and Leafield[3,4] provide a study of the vertical gradient of temperature in the first hundred metres or so and show that the required gradient is exceeded in about 10 per cent. of cases near the ground. Experiments made at Rye measuring temperature and humidity at 4, 50, 155 and 355 ft. have been analysed. These show that the critical temperature inversion of 7°F./100 ft. is exceeded on about 10 per cent. of all occasions in the layer 4 to 50 ft. and on less than 5 per cent. of all occasions in the layer 50 to 155 ft.

Inversions over the sea.—Experiments have been made in Cardigan Bay and the Irish Sea by means of ships using thermocouples attached to booms and to balloon cables to observe temperature and humidity. In the same series of experiments low-flying aircraft also made observations. A preliminary analysis of a series of results showed that in a few cases inversions satisfying the criterion were observed. Inversions will be more rare over the sea than over land from general considerations, if we exclude the first 10 ft. or so where there are marked variations.

Humidity lapses over the land.—The analysis of the Rye records shows that the critical lapse rate of humidity is exceeded on about 30 per cent. of all occasions in the layer 4 to 50 ft., and on about 10 per cent. of all occasions in the layer 50 to 155 ft.

Humidity lapses over the sea.—Humidity measurements have been made in the lower layers over the sea by low-flying aircraft and also from ships, using balloons with psychrometers attached to the cables. Care must be taken in comparing the results obtained by these two methods, since the aircraft measures a mean humidity over a horizontal distance, while the ship measurements are of humidity *in situ*. It is found that the humidity lapse rate over the sea often exceeds the critical lapse rate.

Modified refractive index curves and ray tracing.—The modified refractive index (M.R.I.) is, from p. 75

$$M' = \left(n + \frac{h}{a} - 1\right) \times 10^6$$

and from the approximate ray equation

$$\frac{d^2h}{dx^2} = \frac{dM'}{dh} \times 10^{-6}.$$

Integrating this equation, with suffix $_0$ denoting values at the surface

$$\left(\frac{dh}{dx}\right)^2 - \left(\frac{dh}{dx}\right)_0^2 = 2 \times 10^{-6} (M' - M_0') \quad .. \quad (4)$$

Remembering that dh/dx is the slope of the ray, then if $dh/dx = 0$, the ray is parallel to the earth and

$$-\left(\frac{dh}{dx}\right)_0^2 = 2 \times 10^{-6} (M' - M_0')$$

For a real solution $M_0' > M'$ and the maximum value of $(dh/dx)_0$ is given by the minimum value of M', say $\overline{M}'$. Denoting this maximum angle by α_0 then

$$\alpha_0^2 = 2 \times 10^{-6} (M_0' - \overline{M}')$$

and only those rays emerging at an angle less than α_0 from the transmitter will be bent so that they are at least parallel to the earth. It should be noted that M' is dominated above a certain height by the term h/a and the M' curve will generally slope to the right, with a slope $1/a$ above this height.

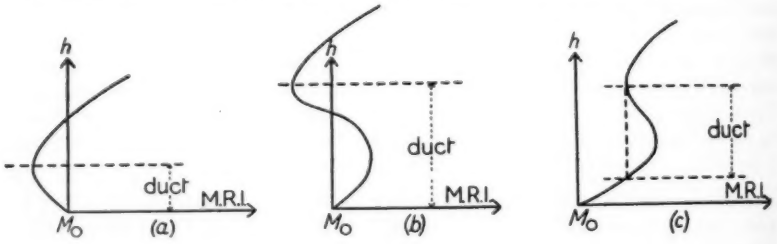


FIG. 2—THREE DIFFERENT TYPES OF M.R.I. CURVES AND ASSOCIATED DUCTS
Errata:—for "M_o" read "M_o"

The M.R.I. curves of greatest interest to the radio meteorologist are those which have a negative slope for some height interval. There are three main types as in Fig. 2 :

(i) M.R.I. lapse from the surface to a certain height after which the M.R.I. increases with height, having an asymptotic slope $1/a$.

(ii) M.R.I. increases with height, then decreases over a range to a value less than the surface value, and then increases again with height. Asymptotic slope $1/a$.

(iii) M.R.I. increases with height, then decreases over a range to a value greater than the surface value and then increases again with height as in (ii).

Using equation (4) we can trace the rays emerging from the transmitter at different angles. Perfect reflection at the lower surface is assumed, although over land this is only very approximate.

Consider an M.R.I. as in Fig. 3 with rays emerging at ground level, and a ray emerging from the transmitter at angle α_1 with the horizontal. Providing α_1 is less than α_0, where

$$\alpha_0^2 = 2\,(M_0' - \bar{M}') \times 10^{-6},$$

then the ray will be bent parallel to the earth at some level where the M.R.I. is M given by

$$\alpha_1^2 = 2\,(M_0' - M) \times 10^{-6},$$

since the angle α the ray makes with the horizon is given by

$$\alpha^2 - \alpha_1^2 = 2\,(M' - M_0') \times 10^{-6}.$$

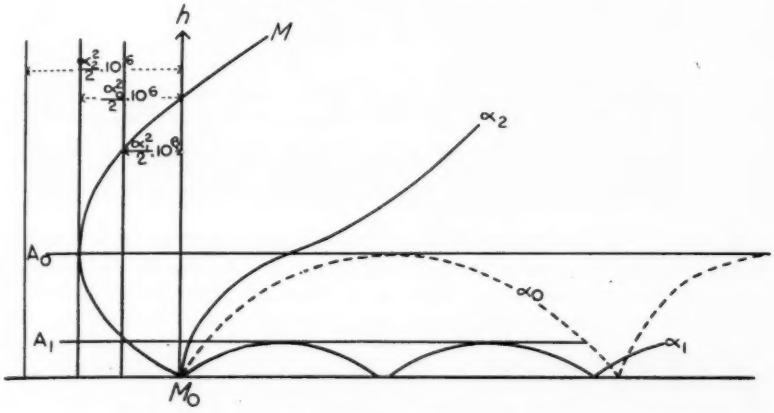


FIG. 3—RAYS EMERGING AT GROUND LEVEL
Errata:—for "M_o" read "M_o'" and for "M" read "M'"

The ray emerging at angle α_1, becomes parallel to the earth at height A_1, and subsequently its motion is governed by reflection at the surface and bending in the layer A_1 to the surface. The ray emerging at the angle α_0 is similarly bent down towards the earth, being parallel to the earth at height A_0, its subsequent path being similar to that of α_1. The ray emerging at angle α_2 is bent towards the earth, but at height A_o is not sufficiently bent to be parallel to the earth's surface ; thereafter it is bent away from the earth, since dM'/dh is positive. Thus all the rays emerging from the transmitter at an angle α_0 or less are trapped in a region below A_o and move around the earth's surface. All the rays emerging at an angle greater than α_0 are not trapped in this manner. The region below A_o is called a duct and the height to A_o termed the duct width.

We can easily establish the duct property in the case represented in Fig. 2(*b*) by similar tracing. The case of Fig. 2(*c*) needs a little care. With the transmitter in the duct the ray-tracing diagram is given by Fig. 4.

The ray emerging at angle α_1, from the transmitter T, where the M.R.I. is M'_0 becomes parallel to the earth's surface at height L_1, is bent down towards the earth in the region where the M.R.I. gradient is negative, and upwards where the M.R.I. gradient is positive until at level L_1', it is again parallel to the earth's surface, its subsequent path being as shown. A ray emerging downwards, at angle α_1, is similarly trapped in the layer L_1L_1'. The ray emerging at angle α_0 is similarly trapped in the region L_0L_0'. The ray emerging at angle α_2

greater than α_0 is not sufficiently bent to be trapped and so is not kept in the confines of the duct. Such a downward ray, reflected at the earth's surface is shown in the diagram by α_2.

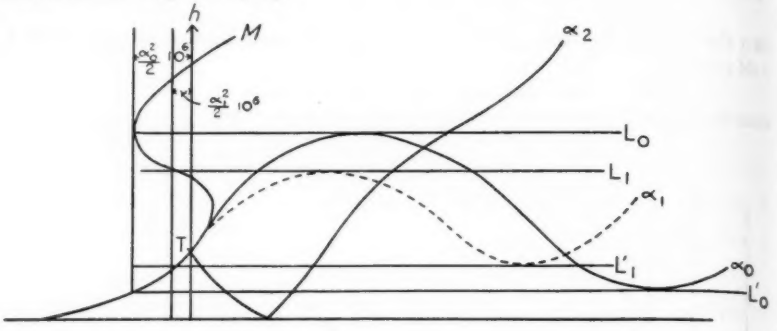
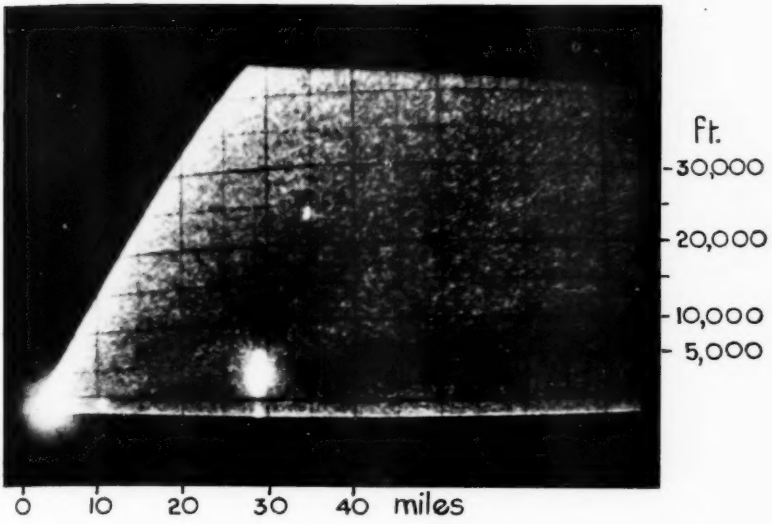


FIG. 4—TRANSMITTER IN THE DUCT
Errata:—for "M" read "M'"

The ray theory outlined above is capable of explaining why electro-magnetic energy is propagated far beyond the normal range. All energy emitted at an angle less than the maximum angle α_0 is trapped and continues around the earth's surface, suffering attenuation until it is too weak to be detected. The energy can be reflected by a target and returned to the source to be detected by a radar unit. The maximum angle α_0 is, of course, very small; for $M' - \overline{M}' = 8M$-units the maximum angle is only $\pm\frac{1}{4}°$ with the pole of the beam. Thus trapping only occurs usually in about $\frac{1}{2}°$ elevations. When rays are trapped a condition of super-refraction is said to exist.

Limitations of the theory.—Although the theory successfully explains why electro-magnetic energy is observed at great distances it fails to draw any distinction between the behaviour of waves of different frequency. The attenuation varies with frequency, but the variation is not sufficient to account for the fact that super-refraction is only observed between about 30 and 30,000 megacycles per second. It also fails to explain why there is a noticeable difference in the super-refractive effects in this range, super-refraction increasing with frequency. Lastly the theory fails to predict field strengths under various conditions, although by ray tracing some estimate of field strength can be made.

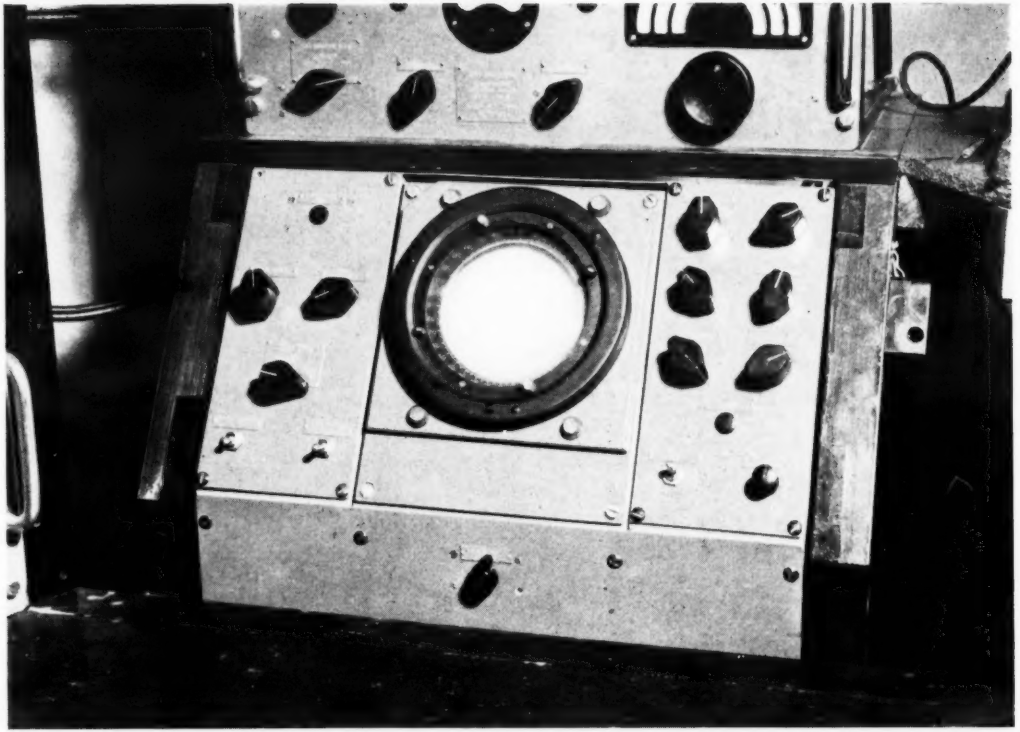
Application of wave theory.—The limitations noted above can be removed by application of the electro-magnetic wave theory[5]. Shorn of the technical mathematics the process is to resolve the electro-magnetic wave into components or modes much as a function may be expanded into a Fourier series. It is found that each mode has a characteristic track width inside which most of the energy is confined, although there is some leakage of energy from the track width. The track width for any mode is a function of the dielectric properties of the medium through which the wave is moving and hence a function of the meteorological variables. The effect of a duct is to suppress the leakage from those modes whose track widths lie inside it and to partially guide those modes whose track widths are slightly in excess of the duct width. Consider only the first mode, and denote it by $H_1(\lambda)$ to indicate that it refers to a wave-length λ, and let it have a track width $w_1(\lambda)$. It can be shown that the track width is a function of wave-length, in addition to being a function of the meteorological



RADAR ECHO FROM A COLUMN OF SMOKE.
Observed on a height-range indicator, East Hill, 1400 G.M.T., August 18, 1949 (see p. 89)

Photo by R.A.F.

CIRRUS AND CIRROSTRATUS ABOVE ALTOCUMULUS
Taken at 10,000 ft. over England, 1400 G.M.T., January 4, 1949



CATHODE-RAY TUBE USED FOR " SFERIC " OBSERVATIONS

Sferics are observed as a " pointer " of light passing through the centre of the screen; the bearing is read on the circular scale 0°—360° surrounding the tube (see *Met. Mag., London*, **76**, 1947, p. 78).

PLOTTING "SFERIC" OBSERVATIONS AT THE CENTRAL FORECASTING OFFICE, DUNSTABLE

Bearings of "sferics" or thunderstorm discharges are made simultaneously at two or more stations in the British Isles. These observations are plotted on the chart as shown, and the location of the discharge is given by the intersection of the bearings.

CATHODE-RAY TUBE USED FOR SFERIC OBSERVATIONS

Sferics are observed as a "pointer" of light passing through the centre of the screen; the bearing is read on the circular scale (360° surrounding the tube (see *Met. Mag., London*, 76, 1947, p. 28).

To face page 81]

Reproduced by courtesy of Sport and General Press Agency Ltd.
Capt. L. A. Holland receiving barograph from Cdr. C. E. N. Franckom, R.N.R., in the court room aboard the *Wellington*

Reproduced by courtesy of Sport and General Press Agency Ltd.
PRESENTATIONS TO LINER CAPTAINS

On the bench listening to Capt. C. E. Duggan replying after the presentation are (left to right) Capt. G. C. Saul, Warden; Sir Nelson Johnson, Director of the Meteorological Office; Air Chief Marshal Sir Frederick Bowhill, Master of Company; Capt. St. G. Glasson, Deputy Master; Mr. W. T. C. Smith, Clerk to Hon. Company. (see p. 89)

variables, in such a way that $w_1(\lambda) > w_1(\lambda_0)$ if $\lambda > \lambda_0$. It is now easy to see why the shorter wave-lengths are more affected by super-refraction than the longer wave-lengths, since for a duct of given width, for a sufficiently long wave-length the track width of the first mode will exceed the duct height and no mode is trapped. As the wave-length is reduced the H_1 wave is trapped, and by further reducing the wave-length the H_2 mode is also trapped, which means that more energy is guided in the duct. On further reduction the H_3 mode is also trapped, giving more guided energy. For example with a uniform lapse of modified refractive index, a duct just failing to trap the first mode of a 10-cm. wave-length transmitter would trap two modes, the $H_1(3)$ and $H_2(3)$ modes, of a 3-cm. wave-length transmittter, and under the same conditions a duct trapping $H_1(10)$ and $H_2(10)$ would trap $H_1(3)$, $H_2(3)$ . . . $H_5(3)$.

The use of the wave theory allows calculations of field strength, but this is a radio problem.

The meteorologist requires the practical knowledge of the order of duct height necessary to produce super-refraction on a given wave-length. This is unfortunately not an easy problem to answer, since it depends upon many variables but a good idea of the order is given by the following approximate formula

$$D = 25\ \lambda^{2/3}\text{ft.}$$

where D is the duct width necessary to trap the first mode of signal of wave-length λ cm, so that for a wave-length of 3 cm. the duct width is of the order of 55 ft. and for 10 cm. of the order 120 ft.

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METEOROLOGICAL OFFICE DISCUSSION

The fourth discussion of the 1949–50 series, held at the Imperial College on January 9, 1950, dealt with the problem of the turbulent exchange of water vapour, heat, and momentum near the ground. The discussion was opened by Mr. F. Pasquill with a description of observational work carried out by a Meteorological Office Unit at the School of Agriculture, Cambridge, during the past three years.

The Cambridge work had been aimed initially at establishing methods of deriving the local rate of evaporation from a land surface. Recognition of the limitations of conventional evaporimeter technique and of the difficulty of making in general a direct measurement of evaporation loss from the ground, had previously led to two meteorological approaches in which evaporation was related to processes of turbulent exchange and energy exchange near the

ground. In order to examine the basic features of these two approaches measurements were made in selected conditions of the water loss over periods of about one hour from isolated but otherwise naturally exposed samples of the surface layer of clayland under grass[1 2*]. These included control measurements in terms of which the adoption of the observed water losses as true evaporation losses was partially justified. The vertical profiles of air temperature, humidity[3] and wind speed were explored in the height range 25–200 cm. and on some occasions, for heat balance considerations, these observations were supplemented[1] by meaurements of the vertical profiles of soil temperature and soil moisture in about the first foot, and of incoming and reflected solar radiation. Long-wave radiation was computed from the Kew radiation chart. Preliminary measurements were also made of the aerodynamic drag of grassland[4].

Summarising the results obtained Mr. Pasquill first referred to the support provided for the validity, in an adiabatic lower atmosphere over grassland, of a law relating drag and wind profile identical with that thoroughly established in aerodynamic work. The eddy diffusivities for momentum, K_m, following from this law were then shown to be in agreement with those for water vapour, K_v, derived from the evaporation and vapour profile measurements in adiabatic conditions. In practice this result leads to a simple formula for evaporation in terms of humidity at two heights and wind speed at two or three heights.

The increases of eddy diffusivity, K_v, in unstable conditions and the decrease in stable conditions were quantitatively demonstrated in systematic relation to the Richardson Number. Since the stability influence decreases rapidly as the ground is approached the relations established for adiabatic flow may be applied in other conditions, as a convenient and reasonable approximation, provided the profiles are observed sufficiently close to the ground[5], say below 50 cm. A general *a priori* quantitative explanation of the stability influence did not however seem possible at present. A useful result followed from considerations of the empirical wind-profile law recently put forward by Deacon, in that values of K_m computed from this law were in good agreement with those observed for K_v in unstable conditions, though in stable conditions a considerable disparity appeared.

The heat-balance observations lead to values of the eddy diffusivity for heat, K_h, sensibly equal to those of K_v, in stable conditions but in unstable conditions K_h was systematically the greater. The latter feature is qualitatively consistent with the broader implications of Priestley and Swinbank's modification of the classical treatment of the turbulent transport of heat. Furthermore, this result means that the conventional heat balance method of estimating evaporation (assuming K_h equal to K_v) may seriously over-estimate the rate of evaporation.

In concluding his remarks Mr. Pasquill pointed out that the work described had been regarded entirely in the light of what might be termed the " bulk property " approach to problems of turbulent diffusion. The more difficult but more satisfying approach, in terms of the intimate turbulent structure of the fluid, was still in a very early stage as far as the atmosphere was concerned, but it was to be hoped that it would not be long before such considerations would be effectively applied to problems of the type which had been discussed.

*The index numbers refer to the list of references on p. 85.

The Director, opening the general discussion, commented on the advance which had been made in the provision of numerical values for the quantities occurring in the equations of turbulent transport, and thought that it was especially interesting to see some experimental support for the Priestley and Swinbank theory that the eddy diffusivities for different physical properties might differ in non-adiabatic conditions.

Mr. Pasquill, replying to a query from the Director, confirmed that the observed evaporation in stable conditions was widely at variance with the values computed from the Deacon wind-profile law. It was clear that careful observations of the drag-wind profile relation in non-adiabatic conditions were required as a first step in elucidating this point.

Dr. G. D. Robinson said he would have liked to have heard more about the actual measurements. Commenting on the difficulty of evaluating gradients from the profile observations he favoured the graphical method adopted in similar work at Kew rather than the numerical procedure adopted in some of Pasquill's analysis. The Kew observations had been used to compute evaporation on the conventional heat-balance method and the aerodynamic method, and the two methods gave the same answer. Furthermore, the observed profiles of temperature and humidity showed good agreement. These results supported the equality of K_h and K_v in both unstable and stable conditions in the height range up to 50 cm., in contradiction to Pasquill's result. The wind profile measurements at Kew had not confirmed Deacon's results. On the question of the flux equations the familiar relation defining the eddy diffusivity had previously been justified by the mixing-length theory of diffusion. If the latter theory was no longer to be accepted then the flux-gradient relation could only be looked upon as an assumption to be justified by observation.

Mr. Pasquill stated that the method of evaluating gradients would not affect the essential implications of the Cambridge results. In any case part of the analysis had been carried out without deriving gradients as such. Whatever analytical approach was used the undeniable experimental " scatter " in the observations appeared ultimately as casual variations in the final results, some examples of which had been given in the opening remarks. In examining the Cambridge results on vapour and heat transfer it was not thought that any critical test of the relative magnitudes of K_h and K_v could be provided by the profile forms alone. The crucial test was provided by the specified absolute magnitudes of the vapour flux and heat flux. Perhaps the difference in the Kew and Cambridge results was partly due to a difference in surface conditions. Following the arguments of Priestley and Swinbank differences in K_h and K_v may appear as a result of a correlation in the temperature and vapour structure in the air. Immediately above a patchy grass surface, such as that on which the Cambridge observations were made, it seemed reasonable to suppose that, relatively speaking, warm air would be dry and cool air moist. With negative gradients of both temperature and vapour pressure this would tend to give more effective upward transport of heat than of vapour, so possibly explaining the $K_h > K_v$ result in unstable conditions.

Prof. P. A. Sheppard commented on the numerical consistency evident in the Cambridge results. Equality of K_m and K_v had also been demonstrated near the ground by observations on the diffusion of smoke. The result was certainly to be anticipated in this region of the atmosphere, but for larger-scale atmospheric processes the influence of the pressure field would be important and the situation

might then be different. As regards the equality of K_h and K_v demonstrated in stable conditions and the difference in unstable conditions, was this result an indication of a change in the physical process of turbulent exchange ?

Mr. Pasquill replied that he had not considered the matter on those lines but that his previous tentative argument could equally be applied to the stable case. In the Cambridge observations, however, the vapour gradient was still negative, while the temperature gradient was of course positive, and if a correlation of the type suggested still held it was conceivable that the vapour flux (upward) and the heat flux (downward) would be influenced to a similar degree, so maintaining approximate equality in the apparent values of K_h and K_v.

Mr. R. W. Gloyne queried the validity of applying an evaporation formula established by measurements with a saturated top soil to occasions when the top soil was dry or when plants were drawing water from deeper levels. He asked if in the evaporation measurements any data had been obtained on the influence of the Tufnol container on the temperature of the soil in the evaporimeter.

Mr. Pasquill explained that the formula given for evaporation was exclusively concerned with physical processes in the air above the ground and was clearly independent of the processes of water movement in the soil. Having established it against test measurements of evaporation in selected circumstances it could naturally be taken to apply whatever the conditions of soil moisture. Further, there was no *a priori* reason why it should not apply to a surface under crops, though with the large-scale roughness elements then involved the profile observations would have to be carefully interpreted as regards " zero plane displacement", and the representative nature of observations taken at a single site. No measurements had been made of soil temperature inside the evaporimeters, but it had been verified that the thermal properties of the evaporimeter walls were similar in order to those of soil. A more likely cause of thermal disturbance was the difficulty of ensuring intimate contact at the bottoms of the evaporimeters.

Mr. D. J. Holland drew attention to the formulae now used in computing the concentrations arising from ground-level sources of smoke and vapour. These were still only known to apply to diffusion in the first few metres, and it was important that they should be generalised so as to be applicable to a greater height range. The variation of shearing stress with height would be of particular importance in this connexion.

Dr. F. J. Scrase inquired about the significance of the evaporation measurements made by botanists using the Piché evaporimeter. Pasquill's approach was too complex for normal use.

Mr. Pasquill thought that one might reasonably assume the results to approximate to the evaporation from say a transpiring leaf similar in size and exposure to the evaporating surface of the Piché instrument, but that they could hardly be regarded as representative of the evaporation from a natural assemblage of leaves.

Prof. Sheppard doubted if the indications of the so-called evaporimeters meant anything at all, and thought that much more relianc ecould be placed on indirect estimates from meteorological data. Going back to the earlier discussion on

the flux-gradient relation he said he agreed wholeheartedly with Dr. Robinson in that we could only regard the customary form as a convenient assumption. The "K" approach had now been stretched as far as it would go; some new physical ideas and a re-casting of the whole approach to the turbulent diffusion were required.

Mr. L. P. Smith stated that he had computed evaporation for about 50 stations using Dr. Penman's method. One feature of particular interest which had emerged was that the computed values were entirely consistent with the observed drying out of the Hereford pastures prior to those in Worcester. It was clearly a matter of great economic importance to be able to advise agriculturists on irrigation requirements.

Dr. Robinson pointed out that although few seemed to have a good word for the evaporation tank nevertheless over a long period its indications were consistent with the water engineers' estimates of rainfall minus run-off. Comparisons at Kew between tank indications and heat-balance estimates had shown reasonable agreement over the day-time period when the grass was in a fresh condition, but the tank indications were higher when the grass was dry and withered. Furthermore, the estimated values were usually lower than the tank indications at night.

Dr. R. C. Sutcliffe drew attention to the problem of forecasting evaporation and to the need for estimating evaporation in a practical way. From the latter point of view there seemed to be much in favour of the method used by Dr. Penman, and it was perhaps desirable to link Penman's and Pasquill's methods.

Mr. Pasquill emphasised that the work which he had described had not, in the first instance, been concerned with providing data on the lines required by Dr. Sutcliffe. The object had been to examine the problem from as fundamental a standpoint as possible. In this respect it should be realised that, although Dr. Penman's method appears finally in a form requiring only routine meteorological data, the justification for its general application must depend on a fundamental basis which, however, differed in many respects from that followed in the work which had been described in the opening of the discussion. Having clarified basic principles, then, for practical purposes, there was no reason why one should not reduce equations, which imposed exacting observational requirements, to forms which could be evaluated from cruder data, providing one bore in mind the approximations necessarily introduced.

The Director, referring to the last part of the discussion, drew attention to the important role of soil temperature in any considerations of evaporation in relation to routine meteorological data.

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METEOROLOGICAL RESEARCH COMMITTEE

The seventh meeting of the Instruments Sub-Committee of the Meteorological Research Committee was held on January 26, 1950.

The Sub-Committee considered the Chairman's Report to the Committee and also drew up recommendations for revision of that part of the research programme which deals with instrumental matters.

Among the papers discussed was one by Mr. Shellard[1] dealing with the variation with altitude of the speed correction to aircraft thermometers.

[1] *Met. Res. Pap., London.*, No. 527, 1949.

ROYAL METEOROLOGICAL SOCIETY

At the meeting of the Society, held at 49 Cromwell Road on December 21, 1949, with Sir Robert Watson-Watt in the Chair, the following papers were read.

M. K. Miles—Air motion ahead of warm fronts

Mr. Miles explained how the ageostrophic wind ahead of a warm front was obtained by graphical solution of the equation

$$\mathbf{V} = \mathbf{J} + \mathbf{A}$$

where **V**, the observed wind, was extracted from the 900-mb. level of an upper-wind sounding and **J**, the geostrophic wind, was measured by the pressure gradient on a surface chart. Components of A normal to the fronts were in fair agreement with the frontal speeds, showing that A had some significance.

Comparison of A with the isallobaric and geostrophic vectors indicated a limited relationship. The change in pressure gradient with time along the trajectory of the air (J') was shown to be closely related to A, where

$$|A| = 0{\cdot}78J' - 1{\cdot}0$$

The angle ϕ between A and J' was found to lie between 20° and 50°. It was concluded that the motion of the cold air was not quasi-geostrophic.

Assuming an exponential growth of gradient where $J \propto e^{kt}$, the ratio $|A|/J'$ was found to agree with the calculated value when k lay between 0·4 and 0·45 hr.$^{-1}$. Allowing for possible errors, ϕ was found to be about 45°. These results were illustrated graphically by Mr. Miles.

Among points raised in the discussion, Mr. Matthewman disagreed with the growth of gradient used by Miles, and produced smaller values of k. Mr. Douglas pointed out the difficulties of measuring isallobaric and ageostrophic winds, and said that investigation into cold-front motion was also required. Mr. Sawyer pointed out that a component of A was still unexplained and wondered why exponential growths were assumed. Dr. Sutcliffe was glad that acceleration and not friction seemed to be responsible, though the complete dynamics had not yet been worked out.

In reply, Mr. Miles said that growths other than exponential do not fit. Friction was a small effect.

F. H. Ludlam—The composition of coagulation elements in cumulonimbus

Mr. Ludlam said that in a cumulonimbus cloud the initial concentration of ice crystals is low compared with that of liquid water droplets. Ice crystals should not interfere with each other's growth. Water contents of clouds may be obtained from an aerological diagram; summer clouds will contain about 7 gm./m.^{3} compared with winter values of 1 gm./m.^{3}.

When an ice particle reaches a diameter of 1 mm. and the water content of the cloud exceeds 1 gm./m.^{3}, further growth will be controlled by coagulation with water drops in the path of the particle. A film of water on the particle will freeze liberating latent heat. The temperature will not rise to 0°C. since heat is lost by conduction to the surroundings and by evaporation from the water surface.

Dr. Ludlam then showed how the heat loss will be greatest when the water surface is at 0°C., and illustrated graphically the critical concentrations of water vapour required to produce a wet growth for various temperatures and water-drop sizes. Small elements less than 1 mm. thick and large elements associated with low water content can grow as frozen structures. When the water content is high, large elements can accumulate water down to temperatures of about −30°C. Drops may also break up if they become too large. The layered appearance of hailstones can therefore be accounted for without complex vertical motion.

The presence of coagulation elements may throw light on problems relating to thunderstorms and radar echoes. "Splintering" of large complex ice crystals is associated with the development of thunderstorm charges. It seems likely that thunderstorms will develop when cloud temperatures are below −32°C., otherwise the large particles would be wet coagulation products.

Dr. Wexler queried the size and growth of the particles and wondered how diffusion could account for them. Mr. Fournier d'Albe asked if the products had time to grow.

Mr. Ludlam, replying, said that in view of the high water content, he assumed large droplets; these would be picked up by the falling ice particles. A few minutes was sufficient for the growth of coagulation elements.

OFFICIAL PUBLICATION

The following publication has recently been issued:—

METEOROLOGICAL REPORTS

No. 4—*Aviation meteorology of the route Marseilles—Castel Benito*

This report describes the climate of the air route from the south of France to Tripolitania with special attention to factors affecting aviation. The various types of weather situation are described and their relation to the movement of depressions and fronts across the route. Visibility, cloud, wind, rainfall, etc., are discussed individually and notes on local conditions at airfields are included. A number of climatic tables are given.

The broad picture presented is one of settled fine weather in summer with only brief interruptions affecting the north. In winter disturbed conditions are as common as over north-west Europe, but the extensive low cloud and areas of bad visibility, frequent over north-west Europe, rarely occur for long over the Mediterranean. On the other hand, convectional weather, showers, cumulonimbus cloud, thunder and turbulence are just as common over the route in winter as over north-west Europe.

LETTER TO THE EDITOR

Luminous night clouds

In a very interesting article on these clouds in the *Meteorological Magazine* for December 1949, Mr. Paton refers to the two alternative suggestions which have

been made regarding the composition of these clouds, *viz.* (*a*) that they are clouds of dust of either volcanic or cosmic origin or (*b*) that they are clouds of water (ice) resembling cirrus clouds. It seems to me that Mr. Paton's own observation, which he describes in the article, goes far to decide this question. Describing the appearance of the clouds on July 10–11, 1949, he says that the main cirrus-like clouds showed " only a slow change in form with time " but " by contrast, the background showed continuous change, sometimes appearing as a perfectly uniform sheet, then suddenly developing within itself thin parallel waves. . . ."

It is difficult to see how a layer of dust could change its appearance as this background cloud did, but such changes would be readily understood if it was a water cloud and indeed similar changes can constantly be seen in cirrus clouds. If the background cloud were a water cloud, there is strong presumption that the whole cloud was also a water cloud.

G. M. B. DOBSON

Watch Hill, The Ridings, Shotover, Oxford, December 29, 1949

[While observing the development and disappearance of parallel waves in the thin background of the night clouds, so very like the changes that occur in cirrus clouds, I felt convinced, like Dr. Dobson, that they could be explained only by assuming that these were water clouds. Later reference, however, to Professor Brunt's account and photographs* of artificial smoke clouds suggested that, despite the vast difference in scale, such changes might occur in air-borne dust through wind shear. Perhaps the observed thin background is simply dust moving vertically to join the main clouds at the discontinuity at 80–90 Km. and the waves develop on passage through a region of rapid shear? It may be significant in this connexion that the background is most dense at lower elevations. Examination of the photographs shows that the solid cloud streaks stand out against an almost dark background in the upper portions of the cloud mass.

Then, if these were water clouds, would not many of the particles, slow though their rate of growth must be, eventually develop to the size when selective scattering of the blue would cease? Yet during the whole period of three hours while we observed them, the clouds remained brilliantly blue in colour. Only the edges and thinner parts appeared grey-white, but presumably this was due to low luminosity, below the threshold of colour perception. Investigation of the nature of changes in the profile of the spectrum during a display would reveal if growth of the particles beyond dimensions of the order of the wave-length of visible light actually occurs—J. PATON].

NOTES AND NEWS

Universal Decimal Classification
551.5 Meteorology

The Secretariat of the International Meteorological Organization has drawn our attention to the statement which appears at the end of the first paragraph on page 60 of the *Meteorological Magazine* for February 1950, where it is stated that the revised Section 551.5 of the Universal Decimal Classification, as agreed between the International Meteorological Organization and the International Federation for Documentation, will be published as an amendment to I.M.O.

*BRUNT, D.; Natural and artificial clouds. *Quart. J. R. met. Soc., London*, **63**, 1937, p. 277.

Publication No. 61. The Secretariat point out that the form in which this information will be published has not yet been decided, but that it will not be as an amendment to Publication No. 61. We will inform our readers about the way in which the I.M.O. decide to publish this information as soon as the matter has been decided.

Meteorological occasion at the Honourable Company of Master Mariners

On January 18, in the colourful Court Room of the *Wellington*, Headquarters' ship of the Honourable Company of Master Mariners, an impressive little meteorological ceremony took place. The occasion was the presentation of barographs by the Director of the Meteorological Office to three master mariners, in recognition of long and meritorious service as voluntary meteorological observers (see photographs facing p. 81).

The recipients were Captain Holland, recently retired from command of the New Zealand Shipping Company's steamer *Rangitiki*, Captain Duggan, now in command of the Canadian Pacific S.S. *Empress of Australia*, and Captain Johnston, in command of the Blue Funnel steamer *Indomeneus*. Captains Holland and Duggan have been voluntary observers since 1921 and Captain Johnston since 1923. During their many years of voluntary work for the Meteorological Office, the records sent in by them have been of a consistently high standard. A similar presentation was made to Captain Patchett of the Cunard White Star Line's steamer *Vardulia*, aboard that ship at Liverpool in December 1949.

The guests included the Marine Superintendents of the three Companies concerned and several other well known figures in the shipping world. Seated on the dais during the ceremony were the Master of the Honourable Company, Sir Frederick Bowhill, the Deputy Master, the Senior Warden and the Clerk, in the ceremonial robes of a City Company, and the Director of the Meteorological Office. Sir Frederick welcomed the guests on behalf of the Honourable Company.

Commander Frankcom, Marine Superintendent, Meteorological Office, in making the presentations on behalf of the Director, congratulated the recipients upon their fine work and stressed the long and agreeable association between the Meteorological Office and the shipping companies concerned, which dated back in one case to 1876. Captain Johnston was unfortunately unable to be present and Captain Glasier, Marine Superintendent, deputised for him.

The Director gave warm thanks to the Merchant Navy for their ever ready co-operation with the Meteorological Office, without which our information about the weather in the oceans, despite the presence of special weather ships, would be quite inadequate.

After the ceremony the Honourable Company entertained the guests to tea.

C. E. N. FRANKCOM

Radar Echoes from Smoke

On August 18, 1949, routine observations were being made at East Hill using the 10-cm. A.M.E.S. Type 21 radar when at about 1400 G.M.T. an unexpectedly bright echo was observed on the P.P.I. display on a bearing of 184° magnetic at a range of 28 miles. Viewed on the height-range indicator the echo appeared as a narrow column of quite high intensity with a top extending to 6,000 ft. (see photograph facing p. 80).

Except for the small vertical extent, the echo was very similar to that from a cumulonimbus cloud giving a heavy shower at that point. The upper air ascents and general meteorological situation ruled out any possibility of cumulonimbus development, or indeed precipitation of any sort, in that area, but in view of the fact that the echo was being received from a point within 5 miles of Northolt confirmation was sought from the Meteorological Office there. Observation at Northolt confirmed that there was no sign of precipitation in that area but an enormous column of smoke was observed from a fire which had just broken out. This column of smoke was rising to a height of about 6,000 ft. and then spreading out under an inversion at that height. Newspaper reports on the following day revealed that the fire originated in a dump containing 800 tons of baled cork which covered an area of $\frac{1}{4}$ acre. Radar responses from this area continued for about an hour before gradually fading away.

Cases of cumulonimbus formation due to fires have been reported occasionally and such cases would undoubtedly have given a radar echo from the cumulonimbus so formed, but I have no knowledge of any other observation in which it is virtually certain that the echo received came from the column of smoke.

R. F. JONES

REVIEWS

Atmospheric Turbulence. By O. G. Sutton. Methuen's Monographs on physical subjects. 8vo, $6\frac{1}{2}$ in. $\times 4$ in., pp. viii + 107. *Illus.* Methuen and Co. Ltd., London, 1949. 6*s.* 0*d.*

One result of the lack of a completely satisfactory theory of atmospheric turbulence is that the most useful theory for any given set of circumstances depends upon the circumstances. Prof. Sutton has performed an extremely valuable task in this little monograph in summarising the present state of knowledge of the subject in a way which brings out the limitations of the various theories without obscuring the broad picture by a multitude of details.

The book opens with two chapters of a general nature dealing with turbulence in general and the meteorology of the lower atmosphere respectively. The third chapter deals with the old *K*-theory and its application to phenomena within the friction layer. The mixing length and statistical theories of turbulence are explained in Chapter 4 with some emphasis upon the distinction between aerodynamically smooth and rough flow. Chapter 5 deals with the diffusion of matter—including evaporation— in terms of the statistical theory and the final chapter discusses turbulence in a variable-density gradient.

This volume can be strongly recommended not only to workers in other fields—for whom the series is intended—but also to the professional meteorologist who is interested in the turbulence of the lower atmosphere.

A. C. BEST

Oscillations of the earth's atmosphere. By M. V. Wilkes. Cambridge Monographs on Physics. 8vo, $8\frac{1}{2}$ in. $\times 5\frac{1}{2}$ in., pp. ix + 76. *Illus.* University Press Cambridge, 1949. 12*s.* 6*d.*

This is one of the first volumes of a new series of " Monographs on physics " issued by the Cambridge University Press and it deals with the subject of the solar and lunar tides of the earth's atmosphere. The first chapter contains an excellent summary of the observational data and the story of the way in which Chapman, Simpson, Pekeris and others disentangled the small pressure variations involved from these data. The author then passes to the mathematical

theory of these tides in terms of the resonance theory in which the tide-producing force and the divergence of the velocity are assumed to have identical periods. The resulting differential equations are complicated and their solutions naturally lead to numerical computations, which are briefly described. In the fourth chapter, the resonance theory is interpreted in terms of the " trapping " of energy by a discontinuity of temperature. If the temperature of the upper part of the atmosphere is less (by an appropriate amount) than that of the lower, energy cannot cross the discontinuity and a resonance oscillation is set up of the required 12-hourly period. The last chapter is devoted to a general discussion of the results, particularly with regard to the effects of successive layers of high and low temperature in the atmosphere up to 180 Km. and to the difficulties found in accounting for the oscillations of the *E* and *F* layers.

The book, especially in its mathematical portions, is not an easy one to read, as might be expected when so much has to be compressed into so short a space. There are some minor defects which could be corrected in later editions. The legend of Fig. 9 is incomplete, the definition of the velocity-component u on p. 26 does not agree with that on p. 41, and the x-co-ordinate on p. 35 is " southerly " not " northerly ". In the fundamental equations (11) and (12) on p. 27 there is made an additional unstated assumption, *viz.* that the contribution of the vertical velocity to the horizontal acceleration is negligible. It is unfortunate that σ is used on p. 42 for the density of the earth whereas elsewhere $2\pi/\sigma$ is the period of an oscillation. Finally the opening sentence of Chapter IV is misleading: it has not been shown, but assumed, in Chapter II that the tide-producing force can be resolved into a set of components, each of which excites a mode of oscillation of the atmosphere. In spite, however, of such minor blemishes, every mathematically minded meteorologist will value this book for its presentation of the resonance theory in so accessible and excellently produced form.

G. C. MCVITTIE

ERRATUM

February 1950, page 56, line 5; *for* G. I. Finch *read* S. Chapman.

METEOROLOGICAL OFFICE NEWS

Message from the Director.—Starting with this number, two pages of the *Meteorological Magazine* will be devoted to Meteorological Office News as a regular feature. One of the objects is to let you know our policy and plans in matters generally, so that you will understand and be able to take an intelligent interest in the part you are called upon to play in carrying out those plans. Another purpose of Meteorological Office News is to tell you what is going on in various parts of the Office at home and overseas—items of interest which you might not otherwise hear about.

We shall try to keep these two pages as human and personal as possible, and to make them serve as a House Magazine in miniature.

All members of the staff are invited at any time to send to M.O.20 any piece of information they think might be of general interest, and to suggest any topic upon which they feel that some guidance or enlightenment would be helpful.

N. K. JOHNSON

Napier Shaw Laboratory for forecasting research.—A fine new building of spacious and pleasing design was occupied by the Forecasting Research Division in January. The building provides accommodation for

the scientific officers and assistants engaged in research at Dunstable. There is also a technical library, a reading and a conference room, and space for the storage of past records in a readily accessible form.

Weather ships.—During 1949 station J was manned by one or other of the British ocean weather ships on 356 days, and station I on 343 days. The stations were left without ships only to land sick members of crews for hospital treatment, or to carry out search for aircraft or ships reported in distress. In one period the more northerly station I was vacated to take up a position nearer the flight track of some U.S.A. jet aircraft flying from Iceland to Scotland.

Scientific assistants.—The continuing shortage of assistants is making it impracticable to provide all the assistants needed at some outstations and in Headquarters Branches, and it is realised that at the under-staffed units both officers and assistants are undertaking a correspondingly heavier share of duties. The Director appreciates their loyal co-operation during a difficult period.

The recruiting campaign for more assistants is being intensified, and it is hoped that the response will lead to a lightening of the burden borne by the staff.

Assistants themselves, and indeed all Meteorological Office staff, can help in the campaign by letting it be known that anyone who has obtained a credit in mathematics or physics in the School Certificate Examination may apply for an assistant post in the Office.

Establishment of assistants.—Those assistants who have not yet been established, and who have had two years' experience of technical work since leaving school (although not necessarily while in the Meteorological Office) should enter the competition for establishment announced in the Meteorological Office Orders. Besides leading to permanent appointments, establishment is the first step on the ladder of advancement, and it also carries improved salary scales and longer annual leave. Assistants who may be in doubt about their eligibility to enter the competition should write immediately to M.O.10. The closing date for applications is March 31, 1950.

Sports and social activities.—The Meteorological Office has so far accumulated a total of 42 points in the effort to retain the Bishop Shield which the Office won last year. The Swimming Championships brought 29 points, and the Cross Country Championships 13.

In the Air Ministry Cross-Country Championships Mr. E. W. Heasman, Assistant at Uxbridge, was first, and Mr. W. Lawson from Middleton St. George was third: in the Team Race the Meteorological Office team of E. W. Heasman, W. Lawson, G. Marriott and G. M. Band was first.

The Meteorological Office, Harrow, has formed a Social and Sports Club which, like the similar club at the Central Forecasting Office, Dunstable, is affiliated to the Meteorological Office Social and Sports Committee. The Officers of the Harrow club are: Mr.R. H. Mathews (President), Mr. G. J. Evans (Chairman), Mr. G. F. Tindall (Secretary) and Mr. L. P. Smith (Treasurer). Besides having teams for netball and football, the club is organising indoor activities for the winter evenings including fencing, table tennis, bridge, chess,etc.

Appreciations.—Letter dated November 30, 1949, from Sir Basil Brooke, Prime Minister of Northern Ireland, to Air Commodore B. V. Reynolds, A.O.C.-in-C., R.A.F., Northern Ireland:

Would you be so kind as to convey to your meteorological officers my appreciation of the help they gave me in forecasting weather conditions on Friday last, and my congratulations on the extraordinary accuracy of their report.

I had to leave Belfast early on Friday morning to travel by road to Derry where I was to receive the Freedom of the City. Lady Brooke was due to arrive from Liverpool on Friday morning and I was most anxious to know whether there was any likelihood of her boat being delayed. Your people, however, were able to assure me that there was no likelihood of fog on the Irish Sea; that there would be a smooth crossing; that road conditions here wou'd be excellent except for the presence of light fog from Dungiven on to Derry.

Every one of their forecasts was 100 per cent. accurate and I am most grateful for their courteous attention to my request.

Letter dated December 19, 1949, from City Engineer, Sheffield, to the Senior Meteorological Officer, R.A.F. Station, Bawtry:

The helpfulness and co-operation rendered by your office in times of snowfall and frost are greatly appreciated in this department and go a long way towards reducing to a minimum the inconvenience suffered by the public of Sheffield at those times. . . .

Radio-sonde work at Lerwick Observatory.—At the time of the early morning ascent on a day this winter the surface wind was 73 m.p.h. during the launching period, with gusts to 89 m.p.h. Both launching cones became unserviceable, but the balloon and its equipment were successfully launched by hand after 3½ hours of strenuous effort.

Retirement.—Mrs. M. Rookledge has retired after seven years as part-time Assistant in M.O.9. Mrs. Rookledge, who was then Miss Bigglestone, previously served in the Climatological Division of the Office from 1915 to 1922.

Future plans.—Even before 1939, the Headquarters Branches of the Office were separated from each other, administration and forecasting in Kingsway, climatology and instruments in South Kensington. In 1939 there was further dispersal, as almost all but the administrative staff were evacuated to the provinces. After the war the climatological, marine and instruments branches reassembled at Harrow, the Central Forecasting Office remained at Dunstable and the other headquarters staff continued at Victory House, London.

It has now been decided to accept an invitation from the Dunstable Borough Council to establish in Dunstable a permanent Headquarters for all but the London administrative staff. It will be some years before the plan can be fully implemented.

WEATHER OF JANUARY 1950

Mean pressure was above 1020 mb. over most of Europe, Canada and the eastern half of the United States, and was nearly 1030 mb. in Yukon and around Bermuda. It was a little below 990 mb. off the south-east coast of Greenland between about latitudes 60°N. and 65°N. The mean was nearly 20 mb. above the average in Yukon and northern Sweden, and 10 mb. below it off the south-east coast of Greenland.

In the British Isles the weather was extremely mild during the first half of the month and really cold during the second half. It was dry over the country as a whole and very dry over much of the southern half of England; for example it was the driest January in Birmingham since records began in 1893 and at Ross-on-Wye since the very dry January of 1898. Apart from a few scattered places sunshine was deficient especially in parts of England and south-east Scotland; at Wakefield it was the dullest month in their record back to 1915.

During the opening days an anticyclone remained almost stationary off our south-west coasts, while Atlantic depressions moved north-east and associated troughs moved east across the British Isles occasioning mild, unsettled weather with rain at times in most areas though falls were slight in the south. By the 6th the anticyclone had moved east and decreased somewhat in intensity, while the north Atlantic was covered by a complex deep depression and a very mild airstream covered the British Isles; heavy rain fell locally in the north-west (2·47 in. at Fort William) but little or none occurred in the south-east. Subsequently pressure continued low over the Atlantic and relatively high over Italy and the central Mediterranean and, during the ensuing days, rain, mainly slight, occurred chiefly in the west and north. From the 10th to 12th a very deep depression in mid Atlantic moved quickly north-east, while an anticyclone over the Bay of Biscay moved north-east and another over the Baltic moved south; further slight rain occurred in the west and north. Temperature reached or exceeded 55°F. locally on a number of days, for example, on the 7th, 8th, 9th and 11th (57°F. at Burnley, and 58°F. at Darwen on the 9th, 59°F. at Harwarden and 58°F. at Leeming, Church Fenton and Huddersfield on the 11th). Minimum temperatures were also very high at times, being as much as 50°F. or slightly above in places.

On the 14th a depression near Iceland moved away east and was followed by a ridge of high pressure associated with an anticyclone off our south-west coasts. By the 16th winds over the British Isles were north-west to north, and cooler, showery weather with bright periods prevailed on the 16th and 17th. By the 18th a fairly intense anticyclone was established over southern Scandinavia with a wedge extending over the British Isles. This distribution was maintained with little change until the 28th, with cold mainly dry weather, though some precipitation occurred chiefly in the north-west and north. On the 28th a trough of low pressure associated with a depression near Iceland caused heavy rainfall in south-west Ireland, and on the 30th the trough moved very slowly east and caused considerable snowfall north of a line from about mid Wales to Norfolk during the early hours. Later on the 30th a small depression developed off south-west Ireland and moved north-east and then north over western Ireland; this was associated with more snow in the northern half of the country. On the 30th snow was 9 in. deep at Forest-in-Teesdale and 6 in. at Ambleside and Chopwell Wood and on the 31st 8 in. at Oakes, Huddersfield, and 6 in. at Bellingham, Bingley and Harrogate. On high ground there was heavy drifting, for example, 4 ft. at Malham Tarn. In the south, moderate rain fell on the 30th and fairly heavy rain in London and parts of south-east England on the 31st. Gales were recorded locally in the west and north on the 28th–31st.

The general character of the weather is shown by the following provisional figures:—

	Air Temperature			Rainfall		Sunshine	
	Highest	Lowest	Difference from average daily mean	Percentage of average	No. of days difference from average	Percentage of average	Percentage of possible duration
	°F.	°F.	°F.	%		%	%
England and Wales ..	61	12	+2·0	70	−8	88	..
Scotland	58	7	+1·5	90	−3	93	..
Northern Ireland ..	57	25	+0·1	53	−7	71	..

RAINFALL OF JANUARY 1950

Great Britain and Northern Ireland

County	Station	In.	Per cent. of Av.	County	Station	In.	Per cent. of Av.
London	Camden Square ..	1·01	54	*Glam.*	Cardiff, Penylan ..	1·36	36
Kent	Folkestone, Cherry Gdn.	1·52	68	*Pemb.*	St. Ann's Head ..	1·35	39
,,	Edenbridge, Falconhurst	1·25	49	*Card.*	Aberystwyth	1·16	36
Sussex	Compton, Compton Ho.	1·42	45	*Radnor*	Tyrmynydd	2·97	47
,,	Worthing, Beach Ho.Pk.	·97	42	*Mont.*	Lake Vyrnwy	3·42	59
Hants	Ventnor, Roy. Nat. Hos.	1·71	67	*Mer.*	Blaenau Festiniog ..	8·73	87
,,	Bournemouth	·78	29	*Carn.*	Llandudno	1·00	41
,,	Sherborne St. John ..	·73	31	*Angl.*	Llanerchymedd ..	1·68	53
Herts.	Royston, Therfield Rec.	1·04	60	*I. Man.*	Douglas, Borough Cem.	2·38	71
Bucks.	Slough, Upton	·70	38	*Wigtown*	Port William, Monreith	2·27	70
Oxford	Oxford, Radcliffe ..	·55	30	*Dumf.*	Dumfries, Crichton R.I.	2·39	74
N'hant.	Wellingboro', Swanspool	·71	42	,,	Eskdalemuir Obsy. ..	4·74	88
Essex	Shoeburyness	1·41	104	*Roxb.*	Kelso, Floors	1·37	78
Suffolk	Campsea Ashe, High Ho.	1·41	77	*Peebles*	Stobo Castle	2·35	78
,,	Lowestoft Sec. School ..	1·26	75	*Berwick*	Marchmont House ..	1·32	59
,,	Bury St. Ed., Westley H.	1·31	73	*E. Loth.*	North Berwick Res. ..	·61	35
Norfolk	Sandringham Ho. Gdns.	·93	48	*Midl'n.*	Edinburgh, Blackf'd. H.	1·26	72
Wilts.	Bishops Cannings ..	·44	19	*Lanark*	Hamilton W. W., T'nhill	2·73	83
Dorset	Creech Grange.. ..	1·05	32	*Ayr*	Colmonell, Knockdolian	2·48	57
,,	Beaminster, East St. ..	·65	19	,,	Glen Afton, Ayr San ..	5·16	101
Devon	Teignmouth, Den Gdns.	·97	33	*Bute*	Rothesay, Ardencraig	3·61	80
,,	Cullompton	·85	26	*Argyll*	L. Sunart, Glenborrodale	6·42	91
,,	Barnstaple, N. Dev. Ath.	1·22	37	,,	Poltalloch	4·78	94
,,	Okehampton, Uplands	2·09	41	,,	Inveraray Castle ..	7·81	95
Cornwall	Bude, School House ..	1·28	42	,,	Islay, Eallabus ..	5·07	108
,,	Penzance, Morrab Gdns.	2·28	60	,,	Tiree	3·83	90
,,	St. Austell	2·89	67	*Kinross*	Loch Leven Sluice ..	2·37	87
,,	Scilly, Tresco Abbey ..	1·32	42	*Fife*	Leuchars Airfield ..	1·23	68
Glos.	Cirencester	·71	28	*Perth*	Loch Dhu	7·05	77
Salop.	Church Stretton ..	·84	32	,,	Crieff, Strathearn Hyd.	2·49	62
,,	Cheswardine Hall ..	·87	39	,,	Pitlochry, Fincastle ..	3·27	93
Worcs.	Malvern, Free Library	·45	20	*Angus*	Montrose, Sunnyside ..	1·54	77
Warwick	Birmingham, Edgbaston	·74	37	*Aberd.*	Braemar	1·74	55
Leics.	Thornton Reservoir ..	·71	36	,,	Dyce, Craibstone ..	2·37	100
Lines.	Boston, Skirbeck ..	1·00	62	,,	Fyvie Castle	1·65	70
,,	Skegness, Marine Gdns.	1·08	62	*Moray*	Gordon Castle	1·61	80
Notts.	Mansfield, Carr Bank ..	1·01	47	*Nairn*	Nairn, Achareidh ..	1·81	100
Derby	Buxton, Terrace Slopes	3·16	71	*Inverness*	Loch Ness, Foyers ..	3·75	89
Ches.	Bidston Observatory ..	·73	34	,,	Glenquoich	10·71	78
Lancs.	Manchester, Whit. Park	1·80	72	,,	Fort William, Teviot ..	9·85	102
,,	Stonyhurst College ..	4·50	105	,,	Skye, Duntuilm ..	4·46	84
,,	Blackpool	1·68	62	*R. & C.*	Tain, Tarlogie House ..	3·28	134
Yorks.	Wakefield, Clarence Pk.	1·40	73	,,	Inverbroom, Glackour..	6.09	113
,,	Hull, Pearson Park ..	1·24	69	,,	Applecross Gardens ..	5·10	93
,,	Felixkirk, Mt. St. John	1·49	75	,,	Achnashellach	8·53	94
,,	York Museum	1·38	78	,,	Stornoway Airfield ..	3·55	72
,,	Scarborough	1·31	65	*Suth.*	Loch More, Achfary ..	7·10	98
,,	Middlesbrough	1·17	73	*Caith.*	Wick Airfield	3·47	14
,,	Baldersdale, Hury Res.	2·09	64	*Shetland*	Lerwick Observatory ..	4·14	97
Nor'd.	Newcastle, Leazes Pk. ..	1·45	73	*Ferm.*	Crom Castle	1·84	55
,,	Bellingham, High Green	2·36	83	*Armagh*	Armagh Observatory ..	1·75	69
,,	Lilburn Tower Gdns. ..	1·59	77	*Down*	Seaforde	1·28	41
Cumb.	Geltsdale	2·94	105	*Antrim*	Aldergrove Airfield ..	1·23	45
,,	Keswick, High Hill ..	4·03	80	,,	Ballymena, Harryville..	2·20	59
,,	Ravenglass, The Grove	2·33	70	*L'derry*	Garvagh, Moneydig ..	3·32	96
Mon.	Abergavenny, Larchfield	·88	26	,,	Londonderry, Creggan	4·42	123
Glam.	Ystalyfera, Wern House	2·97	47	*Tyrone*	Omagh, Edenfel ..	2·73	77

CLIMATOLOGICAL TABLE FOR THE BRITISH COMMONWEALTH, SEPTEMBER 1949

Stations	Pressure		Temperatures							Relative humidity	Mean cloud amount	Precipitation			Bright Sunshine	
			Absolute		Mean values											
	Mean of day M.S.L.	Diff. from normal	Max.	Min.	Max.	Min.	½ Max. and Min.	Diff. from normal	Wet bulb			Total	Diff. from normal	Days	Daily mean	Percentage of possible
	mb.	mb.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	%	oktas	in.	in.		hr.	%
London, Kew Observatory	1017·2	0·0	86	48	71·8	57·0	64·4	+6·9	59·8	81	6·2	0·35	−1·52	6	5·3	42
Gibraltar	1015·9	−1·3	90	63	82·4	68·8	75·6	+3·2	69·4	77	4·0	5·59	—	9	8·1	65
Malta	1018·8	+2·5	93	60	83·0	69·5	76·3	+0·3	70·7	62	2·1	0·00	—	0	10·8	87
St. Helena	1018·0	−0·7	68	51	62·5	54·6	58·5	+1·6	54·8	97	7·7	3·37	+1·12	16	—	—
Lungi, Sierra Leone	1013·4	—	87	69	84·0	73·0	78·5	—	74·5	92	6·9	19·95	—	26	4·7	38
Lagos, Nigeria ..	1013·4	+1·3	87	65	83·6	69·7	76·7	−2·0	75·2	86	7·3	8·46	—	19	3·6	30
Kaduna, Nigeria ..	1010·7	—	88	64	84·5	67·1	75·8	−0·1	70·9	81	6·7	4·77	−6·73	22	6·6	54
Chileka, Nyasaland	1018·6	+0·2	93	55	86·6	63·3	74·9	+2·4	60·4	45	0·9	0·00	−0·18	0	9·5	79
Lusaka, Rhodesia ..	1014·4	+0·5	94	53	89·1	59·4	74·3	+2·8	57·0	38	0·6	0·00	−0·04	0	10·0	83
Salisbury, Rhodesia	1016·9	+0·1	89	47	81·4	54·6	68·0	+2·2	53·8	39	0·3	0·00	−0·20	0	9·9	83
Cape Town	1019·6	+0·5	76	43	65·8	52·1	58·9	+1·0	50·6	72	3·7	2·48	+0·24	14	—	—
Palmietfontein, S. Africa	1018·2	—	87	39	78·1	49·0	63·5	—	50·5	50	1·0	0·79	—	3	10·0	—
Mauritius	1020·1	0·0	84	58	78·8	63·1	70·9	+0·8	62·1	59	4·3	1·40	0·00	18	8·2	68
Calcutta, Alipore Obsy.	1003·1	−1·4	95	74	90·2	79·0	84·6	+1·4	80·3	83	6·0	13·19	+3·18	21	5·2	42
Bombay	1005·7	−2·3	89	73	85·1	75·7	80·4	−0·5	77·2	89	6·6	49·01	+38·33	29	2·7	22
Madras	1005·3	−1·2	94	73	90·7	77·0	83·9	−1·3	75·7	75	6·4	6·74	+1·89	12	5·0	41
Colombo, Ceylon ..	1009·6	−0·3	87	74	85·7	78·1	81·9	+0·7	77·2	82	6·0	3·04	−1·72	18	6·3	52
Singapore	1009·8	0·0	91	73	87·3	75·6	81·5	+0·4	76·3	79	5·3	6·34	−0·45	15	6·2	51
Hongkong	1008·7	+0·4	90	74	86·6	77·0	81·8	+0·8	77·2	83	—	17·02	+7·33	17	7·0	57
Sydney, N.S.W. ..	1019·7	+3·6	81	45	66·4	52·4	59·4	+0·2	54·8	76	4·5	9·04	+6·18	19	5·6	47
Melbourne	1020·0	+4·2	78	33	63·0	43·1	53·1	−1·0	48·3	69	4·9	1·61	−0·83	17	6·5	55
Adelaide	1021·1	+3·6	81	39	66·5	47·0	56·7	−0·5	50·7	53	4·0	0·82	−1·26	8	6·8	58
Perth, W. Australia	1019·9	+1·9	80	39	68·5	48·4	58·5	+0·3	55·0	67	3·0	1·73	−1·69	12	8·2	69
Coolgardie	1019·4	+2·2	89	35	70·8	45·3	58·1	−0·6	49·1	45	3·5	0·58	−0·09	5	—	—
Brisbane	1019·8	+2·2	80	49	73·4	54·9	64·1	−1·1	57·3	64	3·3	2·07	+0·07	11	8·3	70
Hobart, Tasmania	1015·9	+4·9	74	33	61·1	40·4	50·7	−0·3	44·8	59	4·4	0·59	−1·48	11	6·5	55
Wellington, N.Z. ..	1015·3	+1·0	64	35	55·4	44·4	49·9	−0·2	47·4	77	5·1	2·01	−1·96	12	6·7	57
Suva, Fiji	1013·8	−0·5	85	64	78·2	70·0	74·1	−0·4	71·1	87	7·2	17·98	+10·29	29	2·1	17
Apia, Samoa ..	1012·4	+0·6	88	72	86·7	74·1	80·4	+1·5	77·2	79	4·8	7·53	+1·99	21	8·5	71
Kingston, Jamaica	1012·5	+0·3	93	72	89·4	74·9	82·1	+0·6	75·7	76	3·9	6·75	+2·72	9	6·9	56
Grenada, W. Indies																
Toronto	1017·1	−0·7	83	38	67·6	50·7	59·1	−1·2	50·8	88	6·1	3·42	+0·75	10	6·2	50
Winnipeg	1013·3	−0·5	84	25	64·9	42·8	53·9	+0·2	42·8	84	5·4	1·53	−0·69	8	6·3	50
St. John, N.B. ..	1016·3	−1·1	76	40	65·0	51·0	58·0	+2·1	53·8	88	7·8	8·11	+4·37	16	5·6	44
Victoria, B.C. ..	1016·0	−0·4	84	39	60·0	48·3	58·7	+2·6	49·5	89	3·6	0·69	−1·12	5	7·6	60